Science of the Total Environment 651 (2019) 1435–1450

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Floods, landscape modifications and population dynamics in anthropogenic coastal lowlands: The Polesine (northern Italy) case study

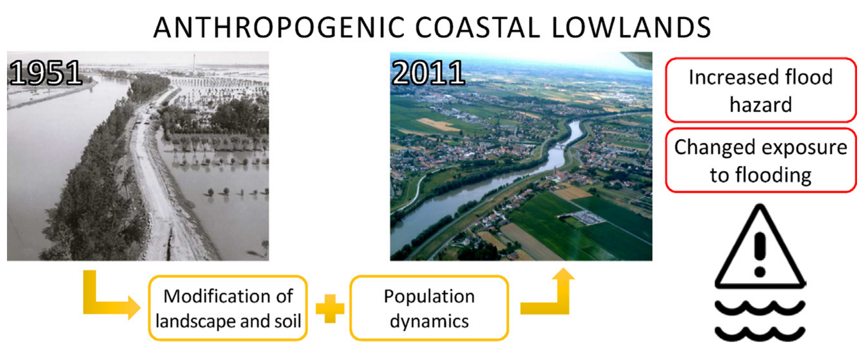
Daniele P. Viero[a,*], Giulia Roder[b], Bruno Matticchio[c], Andrea Defina[a], Paolo Tarolli[b]

[a]Department of Civil, Environmental and Architectural Engineering, University of Padova, Via Loredan 20, Padova 35131, Italy
[b]Department of Land, Environment, Agriculture and Forestry, University of Padova, Agripolis, Viale dell'Università 16, Legnaro 35020, Italy
[c]IPROS Environmental Engineering, Corso del Popolo 8, Padova 35131, Italy

HIGHLIGHTS

- Lowlands are dynamic systems shaped by a wealth of anthropogenic activities.
- Important landscape modifications and land subsidence occurred in the last 60 years.
- Effects on flooding dynamics and on flood hazard were assessed with a modeling study.
- Population spatial distribution changed not in view of reducing exposure to floods
- Land use management and urbanization should account for flood risk properly.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 6 July 2018
Received in revised form 4 September 2018
Accepted 9 September 2018
Available online 13 September 2018

Editor: Ashantha Goonetilleke

Keywords:
Anthropocene
Lowland
Landscape modification
Inundation modeling
Exposure
Flood risk

ABSTRACT

It is widely recognized that the complex relationship between humans, soil, and water has become increasingly complicated due to anthropogenic activities, and is further expected to worsen in the future as a result of population dynamics and climate change. The present study aims at shedding light on the multifaceted links between floods, landscape modifications, and population dynamics in anthropogenic coastal lowlands, using a large flood-prone area (the Polesine Region, northeastern Italy) as a significant case study. Based on the analysis of historical events and the results of hydraulic modeling, it is shown that human interventions on both the landscape and the subsoil have substantially altered the flood dynamics, exacerbating hydraulic hazard. Furthermore, the combined analysis of people and assets exposure to inundation reveals that flood risk is not properly taken into account in land-use planning, nor it is properly understood by people living in areas subject to low-probability, high-impact flood events.

1. Introduction

Investigating the complex interactions between human action, climate, and environment is essential to understand and predict the evolution of flood risk. Interdisciplinary studies focusing on the environment- and human-related dynamics are attracting increasing attention from both the scientific community and the international policy (Di Baldassarre et al., 2013a; Ciullo et al., 2017; Loucks, 2015; Pijl et al., 2018; Sivapalan et al., 2012; Sivapalan, 2015; Sofia et al., 2017; Troy et al., 2015). The analysis of dynamic processes that are driven by the growing human impact needs to move beyond the

* Corresponding author.
E-mail address: daniele.viero@unipd.it (D.P. Viero).

https://doi.org/10.1016/j.scitotenv.2018.09.121
0048-9697/

assumption of stationarity. In this context, insights gained from the recent past are the basis for a deeper understanding of the current conditions, for predicting future scenarios, and for orienting strategic decisions as well (Di Baldassarre et al., 2015).

Throughout the history, humans have long concentrated their activities along major rivers to ensure easy access to a wealth of vital resources (e.g. water, food, transport route). Yet, the erratic behavior of rivers, with major floods wrecking settlements and threatening lives, has been a major obstacle to human development (Di Baldassarre et al., 2013b). In the Anthropocene, heavy human interventions such as deforestation, confinement of rivers, intensive agriculture and urbanization, have substantially altered natural floodplains into anthropogenic environments. With economy rather than ecology as the main driver, recent development has seldom relied on a holistic and long-term vision in which environment and human activities are perceived as part of a unique system. One of its disastrous consequences concerns safety from floods, which are one of the major threat of our time (Blöschl et al., 2017; Doocy et al., 2013; Opperman et al., 2009). This especially holds for highly urbanized lowlands and coasts (Douben, 2006); for example, according to Syvitski et al. (2009), 85% of the deltas experienced severe flooding in the past decades, resulting in the temporary submergence of 260,000 km^2.

The issue of hydraulic risk cannot be regarded as a byproduct of static environmental characteristics. Indeed, lowlands and coasts are complex and dynamic geomorphological systems, in which climatic forcing interplays with socio-economic conditions (Anthony et al., 2014; Di Baldassarre et al., 2013a; Balica et al., 2012; Dawson et al., 2009; Domeneghetti et al., 2015; Minaei et al., 2018; Pijl et al., 2018; Sofia et al., 2017). Human interventions have often intensified, rather than mitigated, flood risk in these environments (Di Baldassarre, 2012; Di Baldassarre et al., 2013a; Parker, 2000; Sofia et al., 2017); this was primarily due to the lack of an integrated system approach to flood risk reduction (Merz et al., 2010). Indeed, it is widely recognized that the historical approach adopted to reduce hydraulic risk, which primarily consisted in confining the river by building up higher and higher levees, actually led to overloading the downstream reaches of fluvial systems (Di Baldassarre et al., 2009). Moreover, in the dynamics of coupled human-natural systems such as rivers and the surrounding areas, levees affect the perception of flood likelihood by filtering small floods, thus encouraging human settlement in areas that, far from being protected, are vulnerable to destruction by low-probability, high-impact events (Ludy and Kondolf, 2012; McNamara and Werner, 2008; Werner and McNamara, 2007).

Anthropogenic impacts on surface water management have been the subject of several studies, focusing on the effects of climate and land-use changes on frequency and magnitude of floods (Bronstert et al., 2002; Camorani et al., 2005; Ferrier and Jenkins, 2009; Fohrer et al., 2001; Hall et al., 2014; Huang et al., 2017; Kundzewicz et al., 2014; Li et al., 2009; Tomer and Schilling, 2009; Whitfield, 2012; Wooldridge et al., 2001; Zhang et al., 2018; Zope et al., 2016, 2017), on the impacts of engineering works aimed at flood control and navigation (Gai et al., 2017; Mitkova et al., 2005; Pattison and Lane, 2012; Spinewine and Zech, 2008; Surian and Rinaldi, 2003), and on coastal and estuarine dynamics as well (Nicholls and Hoozemans, 1996; Silvestri et al., 2018; Simeoni and Corbau, 2009). Less attention has been paid to the effect of anthropogenic landscape modifications on flood dynamics, i.e., on the evolution and features of the flooding process, as it is affected by the interaction with the landscape (Carisi et al., 2016, 2017; Onishi et al., 2014).

The Po River basin (Northern Italy) perfectly fits with this general picture, as it is one of the most anthropogenic and flood-prone regions in Europe (Parrinello, 2017; Roder et al., 2017). Since the Neolithic, this floodplain has been affected by several transformations regarding its topography and hydraulic structure, majorly due to deforestation, population growth, intense industrialization, and climate (Marchetti, 2002; Surian and Rinaldi, 2003). The river system and landforms of the Po plain have been dramatically altered, and its natural setting of the alluvial plain forest has been lost. Several major levee systems and a large network of artificial channels currently shape the river basin, thus stressing the fragile and undersized hydraulic setting that is more prone to flooding than ever before (Guidoboni, 1998; Luino et al., 2012; Simeoni and Corbau, 2009).

The Polesine, extending in the downstream part of the Po River basin, is a 1.800 km^2 flood-prone lowland area that was almost entirely flooded in 1951, when about 8 billion m^3 of water outflowed through three, close each other, bank failures of the left embankment of the Po River (Amadio et al., 2013; Masoero et al., 2013; Turitto, 2004). At present, the Polesine is still exposed to substantial residual risk from major floods (AdBPo, 2008). Interestingly, significant anthropogenic modifications affected the landscape and the subsoil of the region in the meantime. The ensuing topographic changes, mainly related to land subsidence and to raised embankments, are expected to affect the flood dynamics significantly.

For these reasons, in the present study, the Polesine is taken as a significant case study to assess the impact on flood dynamics of anthropogenic modifications to the landscape, here mainly intended as changes to terrain elevation and land features within the region. In a more general view, the study aims at shedding light on the complex relationship between humans, environments, and floods. The analysis makes use of flood inundation numerical modeling. Specifically, two different topographic settings, referring to the 1951 and 2011, are analyzed. The 1951 flood event is used to validate the hydrodynamic model; the same flood event is then simulated using the 2011 topography, and the results are compared to highlight the effects of anthropogenic landscape modifications on flood dynamics. The hazard-based comparison is finally enhanced by analyzing population and socio-economic dynamics, which allows estimating the exposure of people and assets, and its variability in time. A flow diagram describing the methodology of the study is shown in Fig. 1.

2. Materials and methods

2.1. Study area: the Polesine region

The Polesine is a 1800 km^2, nearly flat, low-lying and flood-prone area located in the Northern Italy, (Fig. 2), fringed by the embankments of the Po River from South and of the Adige River from North, and bounded by the Adriatic Sea on the East side. The mean slope of the region is directed eastward; terrain elevations range from +10 m above the sea level (a.s.l.) in Badia Polesine to −4 m a.s.l. close to the Po River delta and the Adriatic coast. Although being formally part of the Fissero-Tartaro-Canalbianco basin, the Polesine region closely resembles a large polder, with a drainage network of about 2000 km of irrigation canals and 80 pump stations for land reclamation (Amadio et al., 2013). The system is firmly stressed during intense precipitation events, and further pressure is due to the sea level rise. Nonetheless, the major source of flood hazard comes from the above main rivers (Fig. 2b) rather than from the inner drainage network.

The main land features that characterize the topography of the Polesine are the levees of navigable channels such as the Canalbianco Channel and the Po-Brondolo Canal, and of the main drainage network (red lines in Fig. 2). Many road and railway embankments (orange lines in Fig. 2) are topographic discontinuities that are expected to affect flood propagation by diverting and blocking floodwaters. Overall, due to the widespread presence of relatively high levees and embankments, distinct sub-basins can be identified which, in case of major flood events, lead to the formation of a sequence of a sort of successive pools.

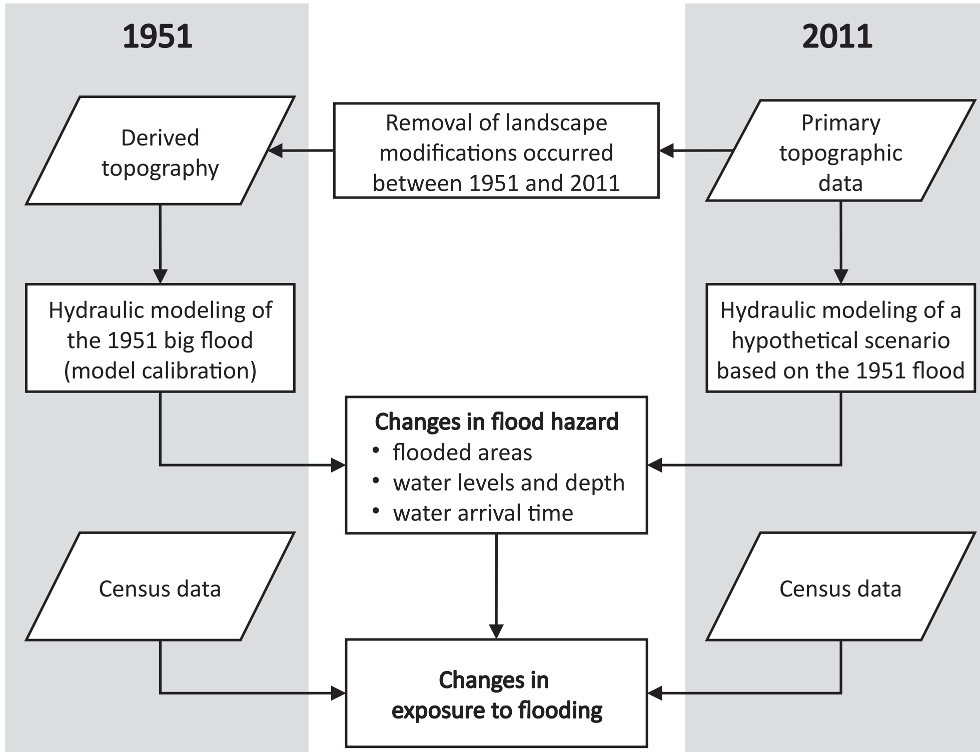


Fig. 1. Flow diagram describing the methodology of the study.

2.1.1. Hydraulic hazard and the 1951 flood

According to the Flood Risk Management Plan drawn up by the Alto Adriatico Water Authority (www.alpiorientali.it) in fulfilment of the 2007/60/CE Flood Directive, the Adige River (Fig. 2) can convey major flood waves safely along its terminal reach. According to the same plan, only small patches of low probability flood-prone areas are identified within the Fissero-Tartaro-Canalbianco basin.

The major source of hydraulic hazard in the Polesine region is related to the Po River, which is the longest and most important river in Italy, having a length of 652 km from the Cottian Alps to the delta protruding in the Adriatic Sea. The discharge ranges between 270 $m^3 s^{-1}$ and 13,000 $m^3 s^{-1}$, with an average of 1470 $m^3 s^{-1}$ (Montanari, 2012). The lands siding the lower reach of the Po River are protected against flooding by a continuous system of embankments, which are as high as 10 m over the surrounding lowlands (Mazzoleni et al., 2014).

In the last century, a series of severe floods affected the downstream part of the Po River (Govi and Maraga, 2005). In 1917 and 1926, embankment failures led to severe flooding nearby Piacenza; in 1951, multiple embankment failures at Occhiobello (Rovigo) caused a catastrophic flooding in the Polesine region; more recently, overflowing were about to occur in 1994 and 2000, with discharges recorded just upstream of the terminal reach of more than 11,000 and 10,000 $m^3 s^{-1}$, respectively.

The 1951 flood event (Fig. 3) left a deep mark on the Polesine region, and on Italy as a whole. According to the Po River Water Authority (AdBPo), this event is taken as a benchmark for both flood risk assessment and flood modeling. For example, peak discharges recorded during the 1951 flood event, increased by 10%, have been used to evaluate potential breaks of the embankments (AdBPo, 2007), and the mapping of flood-prone areas in official plans for flood risk management is primarily based on the flood actually occurred in 1951 (AdBPo, 2008, 2015). Also, the left levee of the Po River, which bounds the Polesine region, is still susceptible to overflowing for floods having a return period of 200 years (AdBPo, 2007, 2008, 2014, 2015).

The present study is mostly based on the 1951 flood event; accordingly, this event is here described in details. The flood occurred in November 1951 was triggered by intense rainfall all over the whole basin of the Po River. Due to average precipitation of 214 mm in 7 days and to the synchronous formation of severe flood waves in almost all the Alpine and Apennine tributaries, a major flood formed along the main reach of the Po River. All the hydrographic stations downstream of the Ticino confluence, approximately 270 km from the Adriatic Sea, measured water levels higher than ever (Amadio et al., 2013; Govi and Maraga, 2005; Marchi et al., 1995). On November 14, water started overflowing the left embankment near Occhiobello, about 90 km upstream of the Po River mouth at the Adriatic Sea, and three, nearly simultaneous breaches formed at Paviole, Bosco and Malcantone (final width of 220, 204, 312 m respectively). The dynamics of the flood event is schematized in Fig. 3a. During the early stage of the flood event, the levees of the Polesella and Canalbianco Channels acted as a barrier against the flood wave, which then was forced to propagate westward; in the first hours of November 15, floodwater began overtopping these levees, and the flood wave expanded eastward towards the cities of Rovigo and Adria. On November 20, the flood wave reached the Adriatic Sea; on November 25, as a result of a controversial political decision, the levees of the Polesella Channel (dashed lines in Fig. 3) were artificially breached to facilitate the draining of the upstream land and to avoid worse scenarios for the city of Rovigo (Lastoria et al., 2006; Lugaresi, 1994; Turitto, 2004). An area of about 800 km^2 was still flooded on December 25, and 350 km^2 were still flooded on February 25, 1952. The city of Rovigo and, among the others, the towns of Adria, Cavarzere and Loreo were evacuated because completely flooded.

On the whole, a total outflow of about 8 billion m^3 caused the flooding of about 1000 km^2 in 38 municipalities of the Polesine region, with water depths up to 5–6 m ponding the whole area

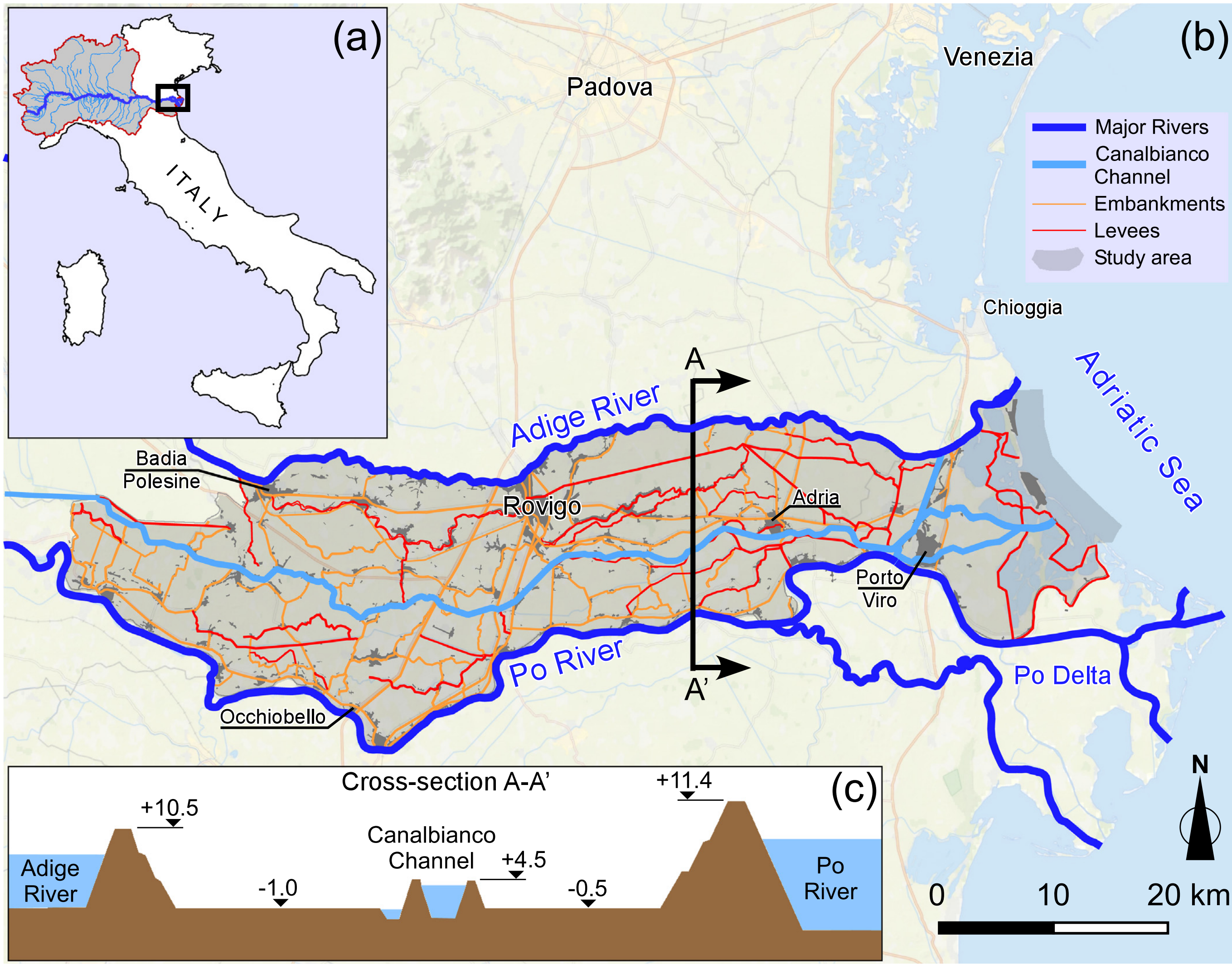


Fig. 2. a) Geographic location of the study area, with the Po River basin shown in gray. b) The Polesine region study area (on National Geographic base map), fringed by the levees of the Po River (South) and the Adige River (North). c) Schematic cross-section (not in scale) of the Polesine region.

for several months (Rossetti, 1957). The flood caused almost one hundred deaths and left 180,000 people homeless (Guzzetti et al., 2005). Nearly 14,000 farms, 5800 buildings, 26 bridges, 140 km of main roads, and 820 km of smaller roads were severely damaged or destroyed. The estimated total damage was of more than 200 million € (uninflated), equivalent to 7.8 billion of today's dollars, and equal to 3.7% of the 1951 gross domestic product of Italy (Lastoria et al., 2006).

2.1.2. *Major anthropogenic changes of the landscape in the period 1951–2011*

The landscape of the Polesine region has been the subject of several anthropogenic changes in the period between 1951 and 2011. In the present study, we consider three major modifications that play a significant role in flooding due to extreme events such as the failure of Po River levees in 1951.

First, the Polesella navigable channel, connecting the Canalbianco River and the Po River before its breakup during the 1951 flood event, was not reconstructed. Note that the Polesella channel, with artificial levees of about 6 m height, acted as a very effective barrier for water flowing eastward toward the sea (Fig. 3).

Second, the elevation of many levees and embankments was significantly lower in 1951 than now, and new ones were built in between. In particular, (i) the banks of the Canalbianco channel are now ~2 m higher than in 1951, as a result of interventions carried out in order to adapt the river to the current waterway functions in the complex navigable system composed by the Fissero, Tartaro, Canalbianco, and Po di Levante channels; (ii) along the Adriatic Coast, the levee for protecting the adjacent lowlands from coastal flooding were raised from 2 to 3 m a.s.l. after the extreme storm surge of November 1966, when the sea level peaked at about 1.80 m a.s.l. (De Zolt et al., 2006; Mel et al., 2014); (iii) as revealed by the analysis of the 1954–1955 aerial images IGMI–GAI (http://idt.regione.veneto.it), several roads were constructed, and most of them involved the creation of new embankments.

Third, the eastern part of the Polesine region experienced significant land subsidence. Aimed at exploiting hydrocarbons, exploration of deep structures under the Po Valley started in the 1930s; the extraction of water mixed to methane from the subsoil significantly increased in the 1950s (Pozzi, 2010), leading to considerable pollution of irrigation canals and anthropogenic land subsidence. The fast lowering of land elevation due to anthropogenic causes, which reached its maximum rate of 300 mm yr^{-1} in the period 1950–1957

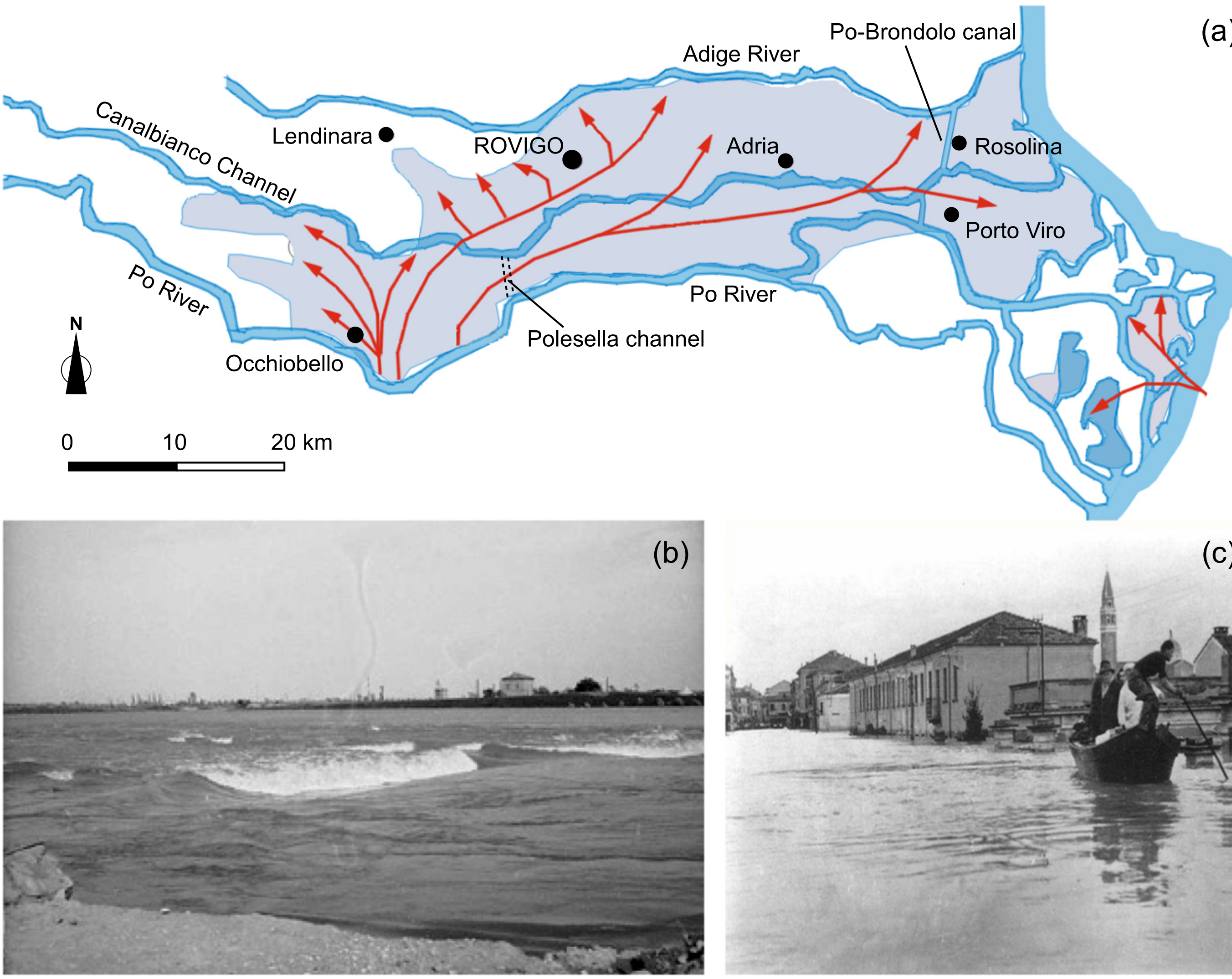


Fig. 3. a) Sketch of the dynamics of the 1951 flood event in the Polesine region. Shaded areas denote flooded land, red arrows denote the inundation directions; b) photograph from the "Archivio fotografico dell'Agenzia d'informazione e comunicazione della giunta regionale dell'Emilia-Romagna" and c) photograph from the "Archivio dei Vigili del Fuoco".

(Caputo et al., 1970; Sestini, 1996), stopped as water extraction was forbidden in 1965 (Teatini et al., 2011). Within the next years, land subsidence continued due to geological mechanisms of soil compaction of the shallowest (30–40 m), highly compressible Holocene deposits (Menin et al., 2008; Teatini et al., 2011); the subsidence rate, which is correlated with the age of the deposits, has remained nearly constant in time up to now. Accordingly, current subsidence rate ranges from 1 mm yr^{-1} at the inland part of the delta, up to 12 mm yr^{-1} at the apex, with an average rate of 2.5 mm yr^{-1} in large part of the region (Carminati and Di Donato, 1999; Teatini et al., 2011).

The effects of both anthropogenic and natural subsidence are exacerbated due to sea level rising and to reduced aggradation in the delta region, which is the major consequence of sediment trapping in the upstream reservoirs and floodplain engineering (Syvitski et al., 2009). For a land that is already below the mean sea level of about 4 m, this critical situation poses severe problems related to both coastal and riverine flood defense, to coastal management, land reclamation, and salinization of subsoils.

Finally, it has to be remarked that, in the last decades, also the minor channel network forming the complex reclamation system the Polesine region has undergone substantial modifications (Sofia et al., 2017; Sofia and Tarolli, 2017). Due to both industrialization of agriculture and urbanization, the storage capacity of the channel network has dramatically reduced, thus enhancing the hydrological response to local rainfall events (Sofia et al., 2014; Sofia and Tarolli, 2017; Viero et al., 2014). Nevertheless, when considering flood events due to levee failures of a major river, overflow discharges can exceed by (at least) one order of magnitude those conveyed by the minor channel network. For this reason, and analogously to similar studies (Masoero et al., 2013), the role of the minor channel network has not been explicitly considered in the present study (see also Section 2.2).

2.1.3. Socio-economical context and dynamics

The Polesine region has a population of about 250,000, of which about 50,000 live in the chief town of Rovigo. The population density, equal to 138 people km^{-2}, is low compared to both the regional and the national mean (268 and 201 people km^{-2}, respectively; data from the national census database, ISTAT). The significant population decrease between 1951 and 1971 (Fig. 4) is mainly due to the disaster of 1951, whereas the ensuing negligible population growth trend can be essentially ascribed to unfavorable social conditions and to emigration to large cities in the north of Italy and other European

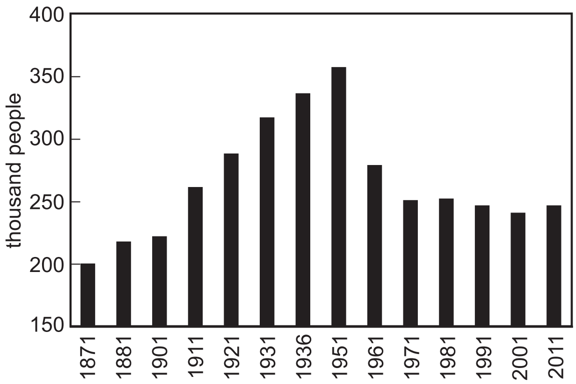


Fig. 4. Population trend in the Polesine region from the national census database (ISTAT).

countries; projections suggest that population density will remain stable for the next 40 years, with a significant increase of the average age (Provincia di Rovigo, 2005). After the 1951 flood event, 100,000 people left the region; the awareness of insecurity and vulnerability adversely affected the job market, slowing down and even arresting the economic development of the area and forcing new jobseekers to move away (Lugaresi, 1994).

The primary sector has a major role in this region, whose territory maintained a marked agricultural vocation and was just marginally affected by the fast industrializing process occurred in the north-east Italian area from the 1970–1980s. The mechanized arable land monocultures (maize, cereals and soy) cover most of the agricultural surface (~ 95%), with little forage and meadow areas supplying the few remaining zoo-technical enterprises. Permanent arboreal cultures are not diffused (~ 4%) since neighbor provinces are more specialized in vineyards and fruit trees cultivation, thus providing a stiff market competition.

On the contrary, fishing and fish farming is a diffused activity on the coastal side of the region, even though the number of fish-farms valleys has significantly reduced since the last century (Unioncamere Movimprese, www.infocamere.it/movimprese). Tourism is increasing business in the region, especially in the coastal area, with almost 2 million visitors every year (mainly during summer), allowing the presence of little to medium size tourism-related enterprises. In conclusion, nowadays the Polesine is a monoculture lowland with few urban areas and reduced natural environments, the latter being mainly located in the eastern part of the delta.

2.2. Topographic data for hydraulic modeling

To support a quantitative comparison between the 1951 and the current flood dynamics in the Polesine region, two different computational grids are set up. Given the far more considerable amount of geographic data available for the more recent scenario rather than that of 1951, the computational grid of the 2011 scenario is first set-up using primary topographic data; successively, the 1951 grid is derived by "subtracting" the major landscape modifications that affected the Polesine topography in the 60 years interval in between.

To set-up the 2011 computational domain, we had to use available data from different sources in order to cover the entire region. LiDAR data (~ 1 m spatial resolution, ~ 20 cm vertical accuracy), provided by the Italian Ministry for Environment, Land and Sea Protection, and "Po Delta" Reclamation Consortium and referring to years 2008–2011, were available only for the area of the Po River delta. Accordingly, terrain elevations in the domain East of Rosolina and Porto Viro (Fig. 5a) were assigned based on these LiDAR data. Topography in the remaining part of the Polesine region is obtained from the digital terrain model (DTM, 5 m spatial resolution, 40 cm vertical accuracy). Levees and embankments were located precisely based on aerial images (50 cm spatial resolution) and Numerical Technical Maps (1:5000) provided by the Veneto region. The resulting topography is shown in Fig. 5b. The extent of the model domain, with an indication of the main land features (hydrographic network, main roads and railways, towns etc.) that are expected to affect flood wave propagation significantly, are shown in Fig. 2.

The computational mesh of the 1951 scenario is then constructed from the 2011 scenario by including the main landscape changes occurred from 1951 to 2011 (Section 2.1.2). Practically, we started from the 2011 computational domain and "subtracted" the major landscape modifications occurred between 1951 and 2011. Specifically, the levees of the Fossa Polesella are added to the mesh, the levees of the Canalbianco Channel and the sea levees are lowered by 2 m and 1 m respectively, and the ground elevation is updated to account for the large land subsidence occurred in the Po delta during this period. The change in ground elevation due to subsidence was estimated separately for the periods 1950–1957 (Caputo et al., 1970), 1958–1967 (Caputo et al., 1970; Carbognin et al., 1984), and 1968–2011 (Teatini et al., 2011), and then superposed to obtain the total variation. Overall, land subsidence in the period 1951–2011 caused a lowering of ground elevations of the order of meters over large areas, with elevation loss up to 3 m (Fig. 5c). The 1951 reconstructed topography is shown in Fig. 5a.

The derivation of the 1951 topography from that of 2011 is a consequence of the lack of enough topographic data referring to 1951. Furthermore, the procedure here adopted is the best way to assess the effect of the lowland changes occurred in the meantime, as systematical errors associated to topographical reliefs taken to so different years are excluded.

The differential map in Fig. 5c highlights the major changes occurred in the region from 1951 to 2011. The variation in terrain elevations due to, respectively, land subsidence and raised embankments can be clearly distinguished as the former is rendered in blue tones (lowering), the latter in orange tones (raising, except for the levees of the Polesella channel that were removed).

In the present study, the focus is on the dynamics of major flood events. Accordingly, hydraulic modeling has to be intended given comprehensive, large-scale analysis. Relatively small landscape features such as minor channels and small obstructions, which are known to affect the flow dynamics at a local scale (D'Alpaos et al., 1995; Hailemariam et al., 2014; Viero and Valipour, 2017), play a negligible role in major flood events like those here considered (Masoero et al., 2013), and thus are not included in the computational grid. Similarly, while uncertainties in the modeled topography can undoubtedly affect the reliability of model results, particularly the extent of flooded areas where water depths are very shallow (say < 50 cm), the global picture described in the following sections, as well as the main conclusions of the study, are nevertheless robust.

2.3. The hydrodynamic model

A wealth of different models is available for flood risk assessment (e.g., Bates and De Roo, 2000; Shafizadeh-Moghadam et al., 2018; Vacondio et al., 2017). In the present study, flood dynamics are investigated using the 2DEF hydrodynamic model, which is an appropriate tool for the purpose of the study given its physics-based and spatially explicit nature. The model solves the full 2D shallow water equations (SWEs) on unstructured triangular meshes. The 2DEF model enforces a statistical subgrid approach for bottom elevations (Defina, 2000; Defina et al., 1994), which allows for a physically based, accurate and stable treatment of wetting and drying processes over very irregular topographies (D'Alpaos and Defina, 2007; Viero et al., 2013). The SWEs are solved using a semi-implicit staggered finite-element method, based on mixed Eulerian-Lagrangian approach

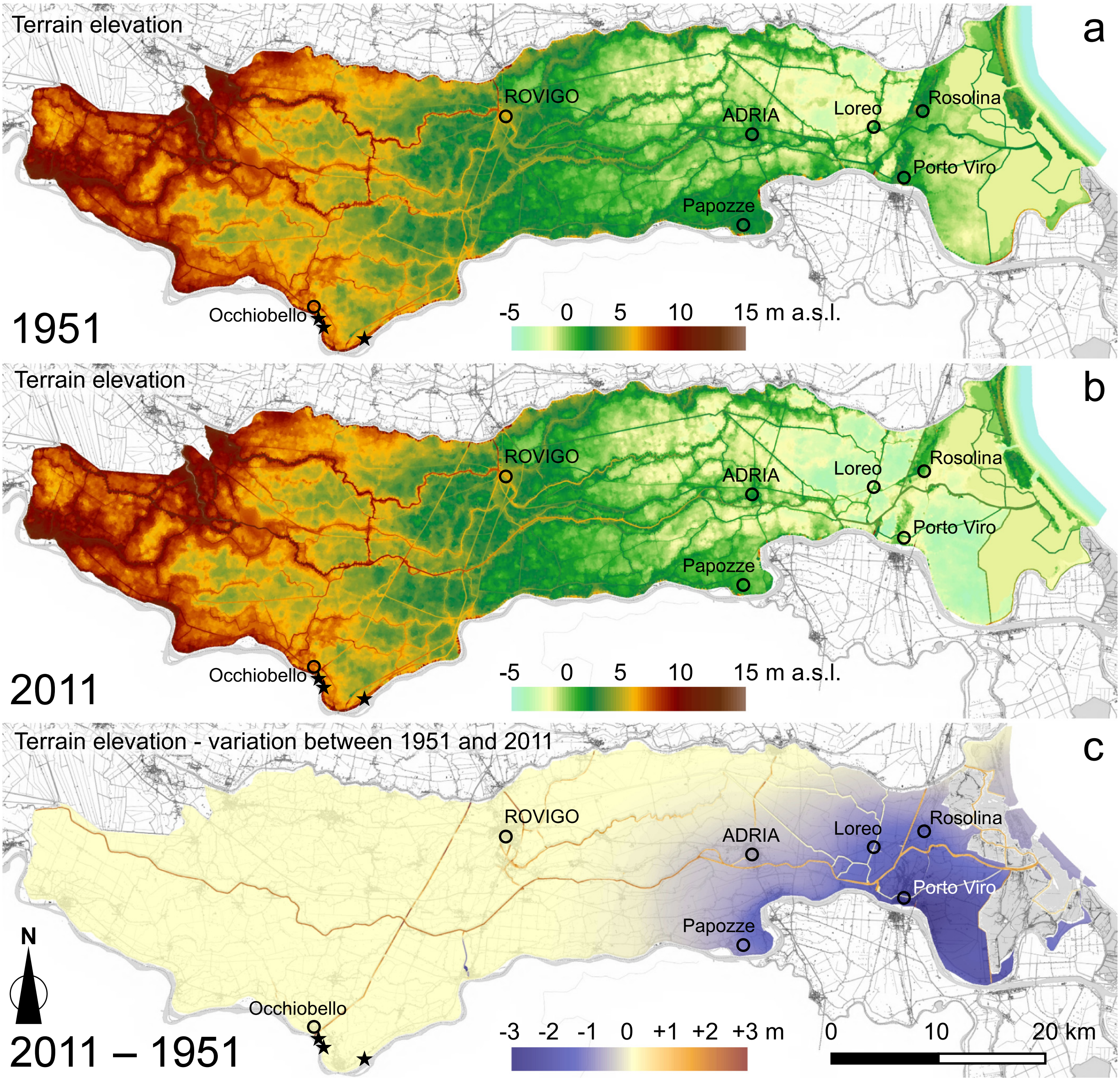


Fig. 5. Terrain elevation (m a.s.l.) concerning 1951 (a) and 2011 (b), and variation in terrain elevation between the two time frames (c); black stars locate the three levee breaches.

(Defina, 2003). The depth-integrated horizontal dispersion stresses are evaluated using the Boussinesq approximation (Stansby, 2003), and the eddy viscosity is computed according to Uittenbogaard and van Vossen (2004). The 2DEF model has been improved in the years to account for, e.g., interactions between free-surface flow and saturated flow in the topsoil layer (Viero et al., 2014), transport of pollutants and evaluation of transport time scales (Viero and Defina, 2016a,b), and anisotropy in bottom resistance due to oriented roughness (Viero and Valipour, 2017). The model also allows for using 1D channels to model the minor channel networks and 1D-links to model levees, sills, and the operations of hydraulic devices such as gates and flow controls (D'Alpaos and Defina, 2007; Martini et al., 2004; Viero et al., 2013; Viero and Defina, 2017, 2018).

The computational mesh covers an area of 1408.6 km^2. It is made up of about 34,000 nodes and 67,000 triangular elements, characterized by a cell-side length that ranges between 300 m in flat areas and 25 m close to topographic features such as rail and road embankments. In the model, terrain elevations are defined on an element-by-element basis. In nearly flat areas, the elevation of computational elements is evaluated as the mean of all the LiDAR and/or DTM points that fall within each triangle of the mesh; the maximum elevation is used in place of the mean to characterize the elevation of embankments correctly (Vacondio et al., 2016).

The model results are quantitatively assessed against surveyed flooded areas according to the method proposed by Bates and De Roo (2000) and Aronica et al. (2002). GIS software is used

to compute the area that the model correctly predicts as flooded (W_1), the area wrongly predicted as flooded (W_0), and the flooded area not predicted by the model (D_0). A first performance index, $P_1 = W_1/(W_1 + W_0 + D_0)$, is a non-dimensional measure of the flooded area correctly predicted by the model. P_1 is equal to 100% when the predicted and surveyed flooded areas perfectly overlap, and penalizes both over- and under-predictions. A second index, introduced by Hunter et al. (2005) to further penalize the fraction of flooded area wrongly predicted by the model, is $P_2 = (W_1 - W_0)/(W_1 + W_0 + D_0)$.

2.4. Exposure evaluation

Exposure is evaluated by identifying people and assets affected by flooding in the two scenarios (1951 and 2011), to ascertain a possible correlation between the two. Demographic and assets data are gathered at a municipality level from the national census database (ISTAT). Then, the percentage increment of the two variables is computed. The zonal statistics of the water depth is calculated for each municipality, extracting the minimum, maximum, and mean values, and the standard deviation for both 1951 and 2011 scenarios. An analysis of variance (ANOVA) is performed to address the implication with the water depth for each municipality and the variations in population dynamics. An equal interval classification is considered for the water depth change, dividing the sample into 0.5 m class breaks based on the value range.

3. Results

3.1. The 1951 scenario

The simulation of the 1951 scenario is used to validate the model, and to shed light on the flood dynamics that are characteristic of the region. Previous studies (D'Oria et al., 2015; Masoero et al., 2013) showed that free outflow occurred through the Occhiobello breaches. This means that the discharge poured into the Polesine region does not depend on the water surface elevation outside the Po River levees. The flooding of the Polesine region can thus be modeled independently from the in-channel flow field. Accordingly, a discharge hydrograph is prescribed at the boundary of the mesh where the three breaches occurred (black stars in Fig. 6). At the eastern open boundary of the mesh, where the sea level is prescribed, water is allowed to leave the computational domain.

Two estimates of the outflow through the breaches are available. The former was derived by Eng. Mainardi, former Director of the of the newly established "Po Delta" Reclamation Consortium, who applied the weir flow relation using measured water levels of the Po River and the estimated width of the breaches as reported in Lugaresi (1994); the latter was derived from the solution of an inverse method based on a 1D hydraulic model (D'Oria et al., 2015, 2016). The shape of the two discharge hydrographs is very similar, the main difference being the magnitude of the discharge and hence the flood volume. In a set of preliminary simulations, we tested the two different boundary conditions and varied the model parameters within an acceptable range. The model results led us to force the model with the outflow hydrograph estimated by Mainardi; the Manning roughness coefficient was finally set equal to 0.033 $\mathrm{s\,m^{-1/3}}$.

Model simulation is run starting from 0:00 of the 14 November 1951 for 26 days. Model results are shown in Fig. 6a (maximum elevation of the water surface) and Fig. 7a (maximum water depth). The model is validated by comparing modeled and surveyed flooded areas (the latter is bounded by a red line in the above Figures). The two performance indexes defined in Section 2.3 are equal to $P_1 = 88\%$ and $P_2 = 86\%$. The visual comparison shows a satisfactory agreement, except for minor discrepancies that are found in the north-western part of the flooded area, where water depths are shallower (i.e., less than 1 m). Here, the minor channel network (not included in the model) and the topographic uncertainties associated to the vertical accuracy of available data (Section 2.2) are deemed to play an important part. The timing of flood wave propagation are also checked against available historical data (Lugaresi, 1994); this is an essential check considering that the flood wave propagation is controlled by the overtopping of many levees and embankments, which is very sensitive to the water surface elevation. The results of the comparison, reported in Table 1, show a very good agreement between collected data and model results, thus confirming the robustness of model results.

3.2. The 2011 scenario and comparative analysis

In the 2011 scenario, the flood dynamics in the Polesine region reflects the major anthropogenic changes of the landscape described in Section 2.1.2. Specifically (see Figs. 6b, c and 7b, c), in the North-West of Occhiobello, water levels are ~70 cm lower, and the flooded area is smaller than in 1951; this occurrence is due to the absence of the banks of the Polesella Channel that significantly hindered the eastward flood propagation in 1951. As a consequence, and also due to the higher elevation of the Canalbianco Channel levees, an area of ~ 100 $\mathrm{km^2}$ West of Rovigo is no longer flooded in the 2011 scenario. On the other hand, the higher elevation of the levees along the Po-Brondolo Canal (dashed line in Fig. 6b) causes a significant increase in water level (~ 70 cm) over large areas (more than 300 $\mathrm{km^2}$) from the city of Rovigo to the Po-Brondolo Canal. The sea levees, which are more than 1 m higher than in 1951, cause about 1 m higher water levels in the region of Rosolina and Porto Viro, close to the Po delta (Fig. 6b). Here, the maximum water depths are dramatically higher than in 1951 because of the concurrent effects of higher water levels and lower terrain elevations owing to anthropogenic subsidence occurred in the last half-century (Fig. 7).

The effects produced by land subsidence and by modified embankment elevations can be distinguished as the maximum water levels were affected almost solely by the changes in embankment elevation, which can be appreciated in Fig. 6c. Indeed, the volume of floodwaters outflowed from the Po River was so large that the maximum elevation of the water surface was not affected by the increased storage volume ascribed to land subsidence in the eastern part of the region. Land subsidence essentially led to increased water depths in the Po delta region (dark blue areas in Fig. 6c).

The differential map of Fig. 7c confirms that, while in the western part of the Polesine region(North of Occhiobello) water depths are about 1 m shallower in 2011 than in 1951, the flooding scenario progressively worsen moving from the city of Rovigo toward the Adriatic coast. It is worth noting that, with water depth up to more than 7 m nearby Loreo and South of Porto Viro, the hydraulic hazard increased dramatically in this area. For example, during the 1951 flood, water depths of about 1 m were recorded in the city of Adria (20,000 inhabitants); the main square of Adria (located 3.4 m a.s.l. in 1951) was not flooded, thus allowing most of the people to meet there while waiting for helicopters bringing food and drugs and, ultimately, to be rescued. In the 2011 scenario, with water levels up to 4 m a.s.l. (1 m higher than in 1951) and, moreover, ground elevation 70 cm lower than in 1951 due to land subsidence, no dry areas could be found in the city of Adria, and water depths greater than 2 m all over its historical center would prevent people from quickly reaching any safe location before the arrival of the flood water, thus causing severe danger of drowning and complicating rescue efforts (Baan and Klijn, 2004; de Bruijn et al., 2015).

When dealing with flood hazard in populated areas, time plays a central role (Balbi et al., 2016; de Bruijn et al., 2015). Water arrival time after a levee failure determines the set of possible countermeasures to be undertaken and, for people, the chances of reaching a safe location. Based on water arrival time, public authorities can develop

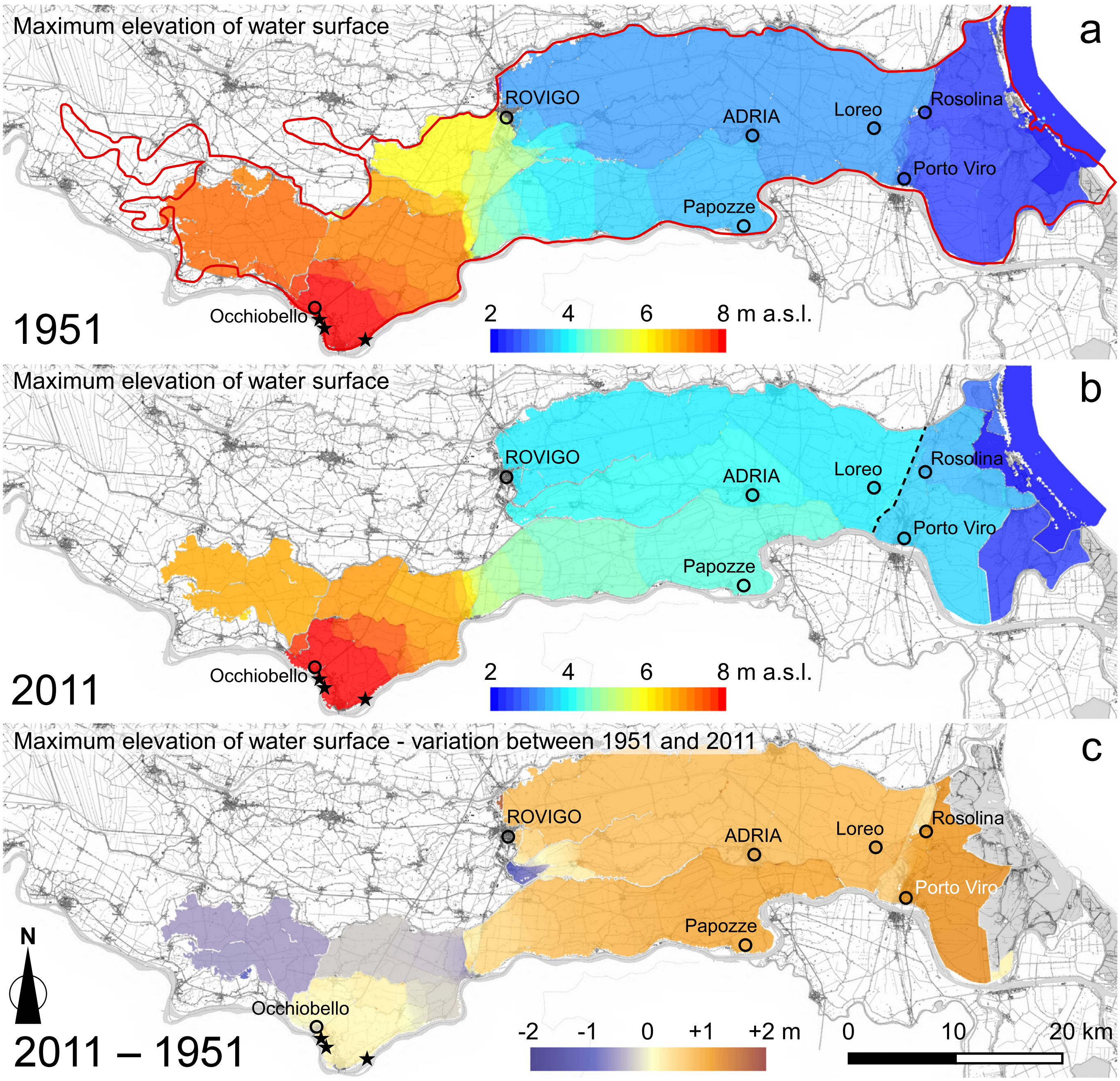


Fig. 6. Maximum elevation of the water surface for the 1951 (a) and the 2011 (b) scenarios, and difference between the two (c). The red line in panel (a) bounds the surveyed flooded area in 1951; the dashed line in panel b denotes the Po-Brondolo canal; black stars denote the position of the three levee breaches.

emergency plans and dispose of evacuation (Molinari et al., 2013). Fig. 8 shows the spatial distribution of water arrival time (computed from when the three levee breaches occurred) and how (and how much) it changed between 1951 and 2011 (Fig. 8c). Flood dynamics are significantly different in the two scenarios. Arrival times were more spatially homogeneous in 1951 than in 2011. Indeed, while in 1951 the levees of the Polesella channel forced major overflowing North of the Canalbianco Channel towards Rovigo, in the 2011 scenario floodwater flows eastward without overtopping the Canalbianco levees; later, barrage effects exerted by the higher levees of the Po-Brondolo Canal cause floodwater to overflow the Canalbianco levees northward, and then to return westward towards Rovigo.

In terms of water arrival time, the 2011 scenario is undoubtedly less critical in the main town of Rovigo (+5 days to be reached by floodwater) compared to that of 1951; however it is significantly worse for the strip of land confined between the Po River and the Canalbianco Channel since, e.g., water arrival time is shorter by 18 h in Papozze (−30%), by 10 h in Adria (−17%), and by up to 20 h (−27%) in its periphery and in Loreo as well (Fig. 8c).

In 1951, the three breaches were closed about one month after they occurred; the time needed to close levee breaches is likely smaller nowadays than in 1951, thus entailing smaller volumes of floodwater poured into the Polesine region. On the other hand, the volume of floodwater to be pumped away to dry up the land lying

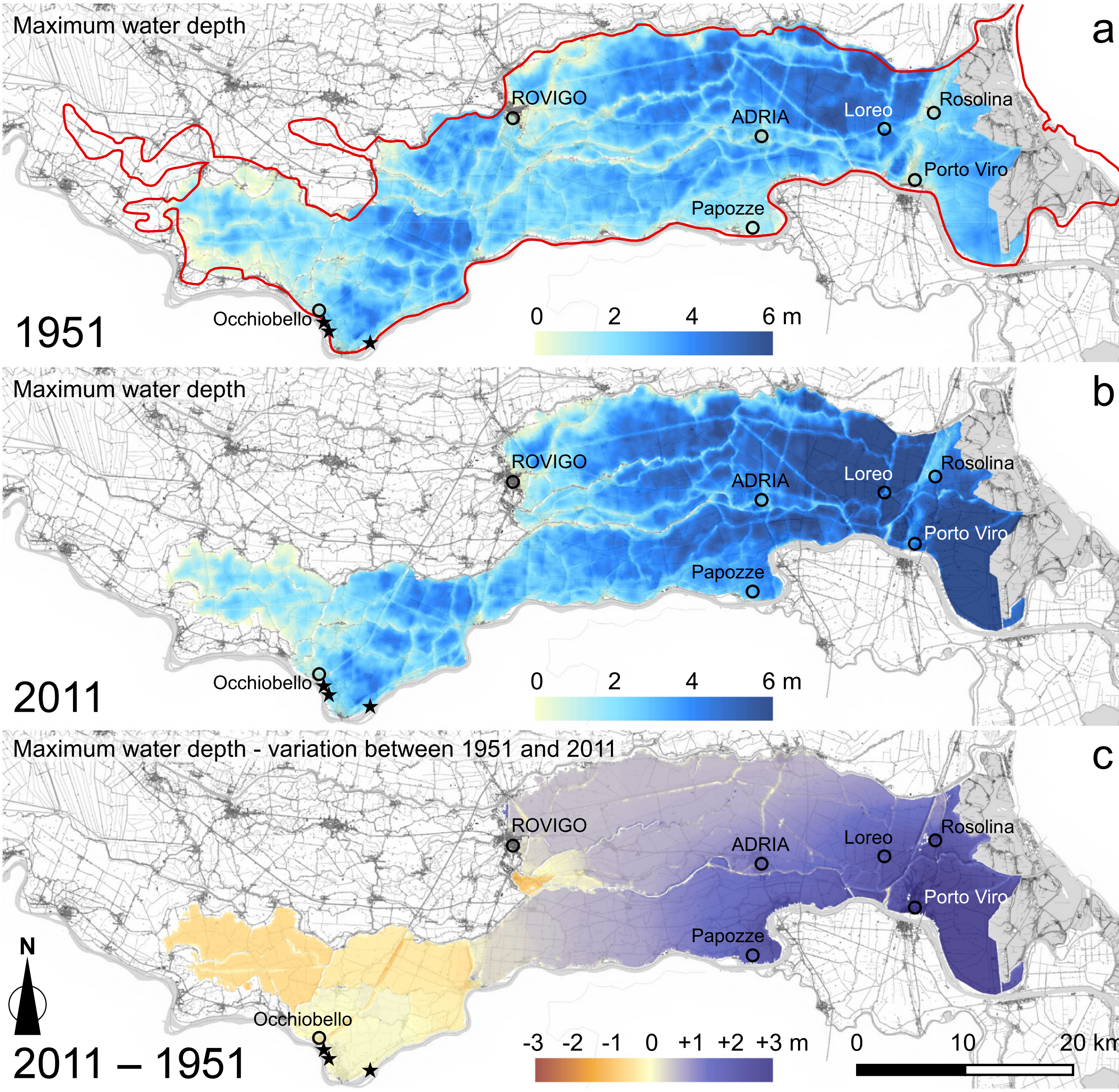


Fig. 7. Maximum water depth for the 1951 (a) and the 2011 (b) scenarios, and difference between the two (c). The red line in panel (a) bounds the surveyed flooded area in 1951; black stars denote the position of the three levee breaches.

Table 1
Comparison between real and modeled timing of the flood propagation over the Polesine region.

Chronology of the 1951 flood	Recorded timing	Modeled timing
Overtopping of the levees of the Polesella and Canalbianco Channels	15 Nov, 5–6 a.m.	15 Nov, 5:30 a.m.
Flood wave up to the city of Rovigo	15 Nov, 4 p.m.	15 Nov, 4 p.m.
Flooding of Ca' Emo	15 Nov, 11 p.m.	16 Nov, 2 a.m.
Flooding of Adria	16 Nov	16 Nov, 3 p.m.
Flooding of Rosolina	18 Nov	18 Nov, 0 a.m.
Sea levees overtopped	20 Nov	19–20 Nov

below the sea level is now $458 \cdot 10^6$ m^3 compared to $205 \cdot 10^6$ m^3 in 1951 (+125%).

3.3. Exposure and population dynamics

The analysis of variance shows a moderate statistical association between mean water depth and both population and housing changes over the time period. Firstly, associated with an increase in the mean water depth (see classes 1 and 2, Table 2) there was an increase in the number of houses (41.7% in class 1 and 104.2% in class 2). This means that the increased number of houses is specifically consistent in areas known to be flood-prone, representing a higher consumption and demand of build-up areas since the 1951

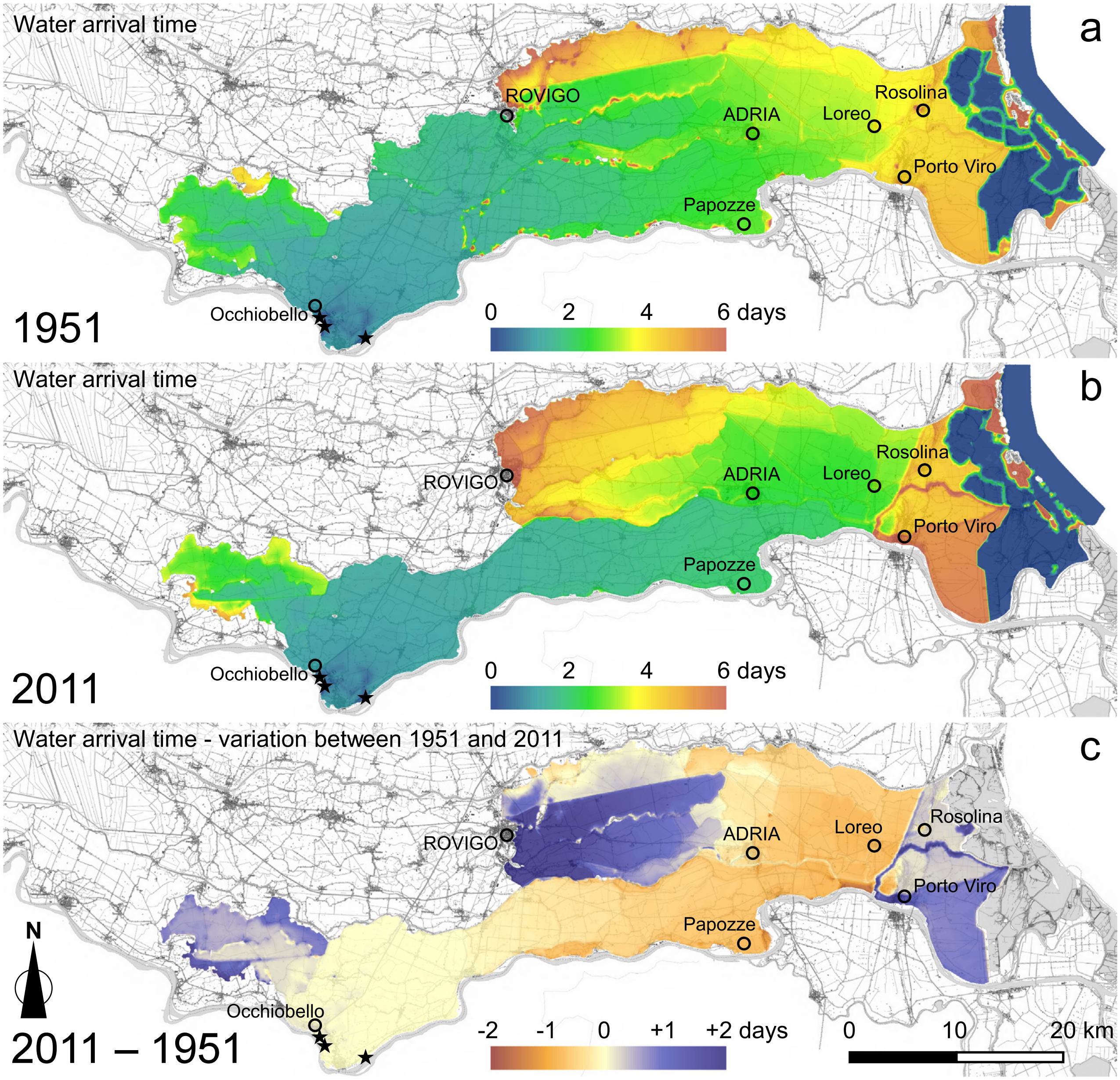


Fig. 8. Water arrival time (since the breach opening) for the 1951 (a) and the 2011 (b) scenarios, and difference between the two (c). Black stars denote the position of the three levee breaches.

(Aubrecht et al., 2011; Koks et al., 2015). The effects of rising urban areas coupling with flood exposure create a challenge for risk financing, at both a household and a national level. Firstly because the private insurance market in Italy for flood protection is almost absent (Gizzi et al., 2016), and secondly because the Government has not created a protection system in support of the private one. Floods burdens are not only exacerbated by these aspects but also by population dynamics affecting the resulting exposure (Jongman et al., 2014; Tanoue et al., 2016). In accordance with this research, the 1951 massive migration caused a decrease in population, easily traduced into a decreased exposure. However, it has been found that lower levels of depopulation correspond to classes 1 and 2 of water depth change (a depopulation of 41.6% in class 1 and 9.4% in class 2). In simple words, this means that fewer people abandoned the most hazardous areas resulting that those that at the time did not migrate remained exposed to flood risk up to present days. Considering the broader picture, the Polesine region is one of the regions (based on the Northern Italy floodplain) suffering the most from a social vulnerability to floods (Roder et al., 2017). Here, the national census and subsequent statistical analyses evidenced the most substantial burden defined by an economic fragility derived by the lowest rate of employment and by the high pressure on the agriculture sector. The high dependency individuals have with the environment (Tiraboschi, 2014) put them in higher jeopardy during a flood event.

The situation described so far can depict a strange correlation between the increased number of properties and the reverse trend for the population growth. This might be due to different, interrelated reasons. After the major flood, some rural units have certainly been abandoned and never recovered, seeing more convenient constructing new urban areas. In parallel, the necessity of building new urban areas might be correlated to people's necessity to live closer industrial and urban nuclei, abandoning slowly the farming activities towards new businesses. In fact, according to Bühnemann et al. (1979), in the Rovigo province after 1951, there was an increase

Table 2
Class variations according to the percentage of houses and population between 1951 and 2011. In brackets the fraction percentage of variation per class. Eta-square effect size is also shown.

Class	Water depth change (m)	House variation (%)	Population variation (%)
1	>0.5	41.7 [−5.2]	−41.6 [−7.2]
2	0–0.5	104.2 [10.0]	−9.4 [10.9]
3	0–−0.5	24.8 [−4.1]	−43.0 [−3.1]
4	< −0.5	26.1 [−0.7]	−43.6 [−0.6]
	Eta-square (η^2)	0.05	0.07

in the number of “unproductive” areas over the whole of the flat country, which is attributable to substantial urbanization. A third explanation might be ground on family size. Now, more than in the ’50s, families are smaller, sometimes composed of single individuals (Bianco, 2015). This probably has risen the need for more residential units. However, the important point is that the new urban sites have been built-up in the actual higher hazard zones according to the correlations in Table 2.

The municipalities highly exposed to flooding are Porto Viro, Papozze, Loreo, Adria and Rosolina, localities emerging even in Fig. 7.

4. Discussion

4.1. Main implications of the study

Based on the results of the study, a number of interestingissues deserve to be discussed.

First, anthropogenic landscape modifications, such as the construction (or removal) of embankments or land subsidence, can significantly affect flood dynamics and hydraulic hazard in lowland areas. Therefore, as a general rule, planning the construction of rail or road embankments and levees in the minor channel network should bear in mind possible interactions with major flood events.

Indeed, the present study confirms that, in nearly flat floodplains and coastal areas, relatively high land features (levees, rail and road embankments) play a critical role in determining the flooding extent. It also suggests that land features aligned with the main course of the river can limit the flood extent; on the contrary, transverse land features can significantly worsen the flooding scenario in the upstream land for huge distances. Hence, the removal of barriers that act to hinder the water flowing toward the sea can be an effective measure to limit flooding extent by creating a sort of route-to-the-sea for floodwaters. By looking at the Polesine region, it seems in fact that the severity of flooding is mostly determined by the elevation of the highest transverse land features.

Secondly, a change in protection philosophy is extremely needed to increase both the safety and the resilience of communities exposed to flooding. The classic concept of ‘flood control’ must give way to holistic practices of ‘flood management’. Examples encompass the adoption of ‘room-for-the-river’ policy aimed at lowering flood levels by giving more room to the rivers instead of heightening dikes and let the flood levels go up (Baan and Klijn, 2004; Dadson et al., 2017; Opperman et al., 2009; Salazar et al., 2012; Sayers et al., 2015), or the purposeful inundation of low-exposed areas in order to protect downstream lowlands from accidental flooding. In this view, Marchi et al. (1995) suggested to reduce the flood risk in the lower Po reaches and the risk of inundation of the Polesine region by reducing the flood discharge entering the lower Po. This could be achieved with the on-purpose temporarily flooding of about 400 million m^3 in a 100 km^2 area immediately upstream of the lower reach of the Po River. With such a measure, the catastrophic flood of the Polesine in 1951 would have been forestalled by flooding a one-tenth area than that flooded in 1951 with only one-twentieth water volume. This change of perspective has already been observed for example in Great Britain (Dadson et al., 2017) and in the Netherlands (Ludy and Kondolf, 2012; Vis et al., 2003), and must undoubtedly be adopted in Italy and worldwide as well. However, the actual implementation of such plans involves distinct economic and social responses (Marchi et al., 1995). Besides proper technical choices, authoritative political decisions are needed (Gober and Wheater, 2015).

These points can be particularly relevant for developing countries with a large range of coastal lowlands (Gupta, 2007; Sarmah and Das, 2018), in which substantial anthropogenic modifications are expected to affect floodplain environments in the near future (Sampson et al., 2016). Indeed, while in developed countries works such as transportation network and structural flood protection measures taken in the past do constrain future choices (Jeuken et al., 2014), planning process benefits from far more freedom in developing countries. This entails plentiful opportunities for reducing flood exposure and for improving urban resilience (Duy et al., 2018). Considering that knowledge transfer from developed to develop countries cannot be direct because of different geographical settings, socio-economic situations, and political situations, governments are encouraged to develop effective and comprehensive flood governance programs (Chan et al., 2018). To avoid or, at least, to minimize detrimental impacts of anthropogenic landscape modifications on flood events, planning must be guided by good practices of integrated flood management in order to balance flood risk, ecosystem, and livelihood objectives (Juarez Lucas and Kibler, 2016).

4.2. Study limitations and future research directions

With regard to the limitations of the study, the modeling analysis uses the 1951 flood event as a base to infer the effect of landscape modifications on flood dynamics. While such an event is undoubtedly representative of what would occur in the case of similar major floods, the effects of landscape modifications on the dynamics lower level of flooding (e.g., Moftakhari et al., 2017, 2018) has not been investigated. As a second point, census data are available only at municipality level, thus preventing a more detailed analysis concerning the ‘intra-municipality’ changes in the spatial distribution of the population. Finally, as a consequence of the above point, also the exposure analysis cannot account for ‘intra-municipality’ variability.

Future directions of research encompass the study of the appropriate morphology of land features (e.g. urban areas, transportation network, farmlands, and canals) in the targeted landscape for reducing flood hazard, or the in depth analysis of the role played by the pattern of transportation network and land features such as canals or farmlands in affecting flood propagation and, in general, hydraulic hazard. This could be done concerning flood events of different magnitude, from moderate flooding to major floods.

4.3. The challenge of boosting preparedness to floods and resilience

In case of severe flood events in lowlands such as the Polesine region, the availability of civil protection plans is pivotal. In this view, the results of the hydraulic modeling can provide a wealth of key information. Knowing the spatial distribution of water depths allow determining what must be done before, during, and after a flood to protect people and properties. Also, water arrival time can be compared with the time needed for evacuation or fleeing, which is influenced by several factors such as the population density, road capacity, distance to safe areas, weather conditions, etc. (de Bruijn et al., 2015). Technical information must be spread to the population in suitable form (Cheung et al., 2016; Feldman et al., 2016), and must be completed with direct and widely accessible communication channels, to make inhabitants aware of both the actual and expected situations, and to allow them to take proper countermeasures or eventually to leave the

region (Balbi et al., 2016; Sorensen and Mileti, 1988). Indeed, social perception of risk is of fundamental importance to enhance preparedness and resilience of urban areas (Bodoque et al., 2016); it can be enhanced by involving citizens in both exploratory studies and decision-making processes (Lane et al., 2011; Luke et al., 2018; Vávra et al., 2017).

Major flood events are relatively infrequent in lowlands as in polders (Baan and Klijn, 2004). This entails negative consequences, which are substantially different in the short term versus long term. Major flood events obviously have significant impacts on population dynamics in the few following years (increased awareness, depopulation, etc.). On the contrary, people and public institutions seem to be unaware of flood-related issues in the long-term. Food risk impacts on property markets disappear rapidly over time (Rajapaksa et al., 2017). Also, the lack of a long-term memory causes flood risk to lose any role in driving urban planning and in the political agenda. This occurrence is further intensified by the fact that anthropogenic landscape modifications take place in 'periods of calm' so that their effects on flood dynamics go unnoticed. These detrimental dynamics is not unexpected considering the overall enhancement of human presence close to streams and rivers during the last decades (Ceola et al., 2015). Furthermore, it demonstrates the need for correct and comprehensive information on flood hazard both to guide land-use planning and to develop effective emergency plans.

People are seldom aware of being exposed to flood hazard. However, it is possible to increase self-consciousness by creating a culture of risk able to improve individual and community preparedness and response during flood events. Information is needed regarding the current and expected flood dynamics that might reflect into tangible protection actions (Thieken et al., 2007). However, preparedness is found to be difficult to achieve, particularly in places where extreme events do not occur frequently (Kreibich et al., 2017; Molinari et al., 2013), causing a lacking public response to warnings (Parker et al., 2007). A useful enhancement could be achieved by strengthening the involvement of citizens in both exploratory studies and decision-making processes (Laborde et al., 2018; Lane et al., 2011; Liu et al., 2018; Vávra et al., 2017; Wehn et al., 2015). If planners, authorities or academics keep concentrating on the probability of occurrence of these events, people will remain, sufferers, whereas if individuals undertake the risk, they will become active agents creating a positive decision-making situation. Of course, this approach to risk is driven by risk attitude, i.e. the decision-makers' inclination for risk-taking that stems from personality and personal cognitive spheres. In this regard, individual's knowledge, perception and action are a successful combination to enhance preparedness and resilience of urban areas (Bodoque et al., 2016). To permit this 'assimilation-engagement', that may be translated as an involvement in the decision-making process in the risk mitigation process, people need to receive information. According to Lugeri et al. (2018), information needs to be simple and not simplistic, to permit individuals to create a geoethics[1], of the environment they live into creating a balanced relationship with their psycho-physical development. Lugeri et al. (2018) argued that "*a communicative strategy that informs the public of the characteristics of a territory (understood as a natural and cultural environment) and the relative operative dynamics, just as one should understand the anatomy and physiology of one's own body, when still healthy, in order to manage and protect it in the best possible way*". It seems evident the need for an integrated watershed management to reduce the hydraulic hazard being sustainable with the environment (Dadson et al., 2017; Salazar et al., 2012; Sayers et al., 2015).

[1] *Geoethics* is the ethical, social, and cultural implications of Geoscience research, practice, and education, representing a new way of thinking about and practicing Earth Sciences (Peppoloni and Di Capua, 2012).

5. Conclusion

The effects of anthropogenic landscape modifications on flood dynamics in lowland areas were analyzed to explore the multifaceted relationship between floods, population dynamics, and human activities such as urbanization, landscape modification, and groundwater exploitation.

The Polesine (North-East of Italy), which is a large lowland area where the residual risk related to major flood events is far from being negligible, was chosen as a significant case study. Since the last great flood of 1951, the Polesine landscape underwent major anthropogenic changes that significantly affected the flood dynamics, exacerbating hydraulic hazard in large part of the region. A comparative analysis between 1951 and 2011, based on the results from numerical modeling, showed increased water levels and depths in large areas, and substantially different spatial distribution of water arrival time. People and assets exposure to flood varied as well within the same period. Population decreased by ~30% in the years following the great flood and remained stable so far; nevertheless, the number of houses is increased by 36% in 50 years. Quite surprisingly, the increase of houses was greater and the reduction of population smaller in areas where the hydraulic hazard has increased, suggesting that population and urban settlements reallocated after the 1951 flood for reasons other than safety from floods.

According to the results of the study, anthropogenic landscape modifications, such as the construction (or removal) of embankments or land subsidence, can significantly affect the flood dynamics and hydraulic hazard in lowland areas. Therefore, as a general role, planning the construction of road embankments and levees in the minor channel network should bear in mind possible interactions with major flood events. In this view, the results from hydraulic modeling can provide a wealth of key information. With a look to the future, effective strategies should be pursued (i) to enhance resilience and preparedness to flood events in lowlands, (ii) to take into account flood-related issues in the long-term land-use planning, (iii) to change the protection philosophy of the protection approach, by replacing the classic concept of 'flood control' with holistic practices of 'flood management'.

Finally, the need of placing flood risk in the center of the public debate is even more critical shortly due to climate change, which is expected to exacerbate flood risk in these areas (Aich et al., 2016; Hettiarachchi et al., 2018; Muis et al., 2015; Simeoni and Corbau, 2009).

Acknowledgments

Daniele Simioni is gratefully acknowledged for his contribution to the set-up of the hydrodynamic model.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

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